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UTAH RESEARCH & DEVELOPMENT CO., INC.

SALT LAKE CITY, UTAH

Subsidiary of Interstate Engineering Corporation, Anaheim, California

NASA Manned Spacecraft Center
Houston, Texas

Structures and Mechanics Division

"EFFECTIVENESS OF ALUMINUM HONEYCOMB SHIELDS IN PREVENTING METEOROID DAMAGE TO LIQUID-FILLED SPACECRAFT TANKS"

CONTRACT NAS 9-3585

FINAL REPORT

December 1964

UTAH RESEARCH & DEVELOPMENT CO.
1820 South Industrial Road
Salt Lake City, Utah 84104

Phone: 846-1301
TWX: 801-531-2680

TABLE OF CONTENTS

SUMMARY

20943

Simulated tests of the effects of meteoroid impact on liquid-filled spacecraft tanks were made by shooting projectiles from a light-gas gun into a titanium window on a pressurized water-filled tank. Aluminum balls 1/8" and 3/16" diameter were used as projectiles at impact velocities of about 22,000 ft/sec. Tank pressure was adjusted and window dimensions were chosen to simulate the biaxial stress in the actual tank walls.

Tests were made of the effectiveness of a shield in protecting the tank from impact damage. The shield consisted of aluminum Hexcell honeycomb material cemented between sheets of aluminum. Impacts were made at angles of 90°, 65°, 45°, 30°, and 20° to the surface of the shield. Shields were spaced 3/8" and 2" from the tank surface.

The shields were found to be effective in shattering the projectile and scattering impact debris over a wide area on the tank skin, particularly with 2" spacing between shield and tank.

The titanium tank walls were tensile tested to determine weakening caused by impact debris in cases where penetration did not occur. It was found that widely dispersed impact debris did not significantly affect the tank strength. Concentrated debris causing obvious damage weakened the material.

Test data and photographs of damaged shields, tank sections, and test specimens are included.

Author

1. INTRODUCTION

This report describes a test program conducted at Utah Research and Development Company to determine the effectiveness of aluminum honeycomb shielding in protecting pressurized liquid-filled tanks from meteoroid-impact damage. Two major problems were of prime concern in this program:

1. To determine the effectiveness of the shields in breaking up and stopping meteoroids impacting at various angles, and to determine the pattern of fragments and spray particles which penetrate the shields and cause tank damage.

2. To determine the extent and seriousness of damage caused to the tank by projectile fragments and spall from the shielding.

Two types of damage were investigated in connection with these problems:

1. Failure of the tank which occurred immediately at the time of impact and was caused by particles penetrating the tank.

2. Possible weakening of the tank by particles which did not penetrate and did not cause immediately disruption of the vessel.

The extent of the damage done by a spray of nonpenetrating particles was assessed by cutting the tank wall into narrow strips and pulling the strips to failure in a testing machine. Results were compared with those from undamaged strips.

A secondary objective of the test program was to measure the magnitude of the pressure pulse in the tank wall in the vicinity of the impact, and to compare this pressure pulse in cases where penetration occurred and when the tank was merely sprayed with fragments.

This report describes the tests performed and the results obtained. The simulation of the actual spacecraft tank is discussed.

2. TEST PROGRAM

The program consisted of shooting high-velocity projectiles from a light-gas gun at simulated tanks and shields. The projectiles used were 1/8" and 3/16" diameter aluminum balls at velocities of 20,000 to 24,000 ft/sec. The tank was fabricated from a 55 gallon steel drum with an 8" x 12" window. The window was covered with a titanium 6 Al -4V sheet*, 0.056" thick and the tank pressurized with water. The honeycomb shielding with constructed of Hexcell** 1" thick with 1/4" cells running normal to the surface. Cell material was 5052 aluminum 0.001" thick. The Hexcell core material was covered on two sides with .016" thick 7076T6 aluminum. Epoxy cement*** was used as the bonding agent. A drawing of the tank and shield is shown in Figure 1, and photographs in Figure 2.

Five angles were selected to test the effectiveness of the shielding, 20°, 30°, 45°, 65° and 90°. Four shots were made at each angle, one of which was without any shielding in front of the titanium window in order to compare penetration of the tank under both conditions. At least one shot at each angle was made with a 1/8" aluminum sphere. All other shots were made with a 3/16" aluminum projectile. The Hexcell shield was spaced 3/8" or 2" from the window surface.

Pressure pulses in the titanium skin were monitored by strain gages mounted on the outside surface of the window. Since strain in the metal was thought to be the best indicator of pulse amplitudes which might be damaging, this type of measurement was chosen in preference to others possible. Strain on the steel tank opposite the window was also measured. Figure 3 shows the circuit and method of mounting.

---

* Titanium sheet from Titanium Metals Corporation of America, 233 Broadway, New York 7, New York. Ti-6Al-4V, 0.056" x 36" x 96" sheets. Heat M-7367: Test X-1654, Test L, Yield 137,500, Tensile 146,000, Elong. 14.0, Bend 4.0, Test T, Yield 137,000, Tensile 143,400, Elong. 13.5, Bend 4.0; Heat D-1457: Test C-5006, Test L, Yield 143,000, Tensile 149,700, Elong. 15.0, Bend 4.5, Test T, Yield 145,400, Tensile 148,500, Elong. 16.0, Bend 4.5; Heat C-6693, Test C-6693, Test L, Yield 130,900 Tensile 141,100, Elong. 12.0, Bend 410, Test T, Yield 139,000, Tensile 145,600, Elong. 13.5, Bend 4.0.

** Hexcell Products, Inc., Inglewood, California.

*** Fuller's Resiweld Epoxy, Adhesive #R7002D Part A, Hardener #R7002D Part B. One part A to one part B.

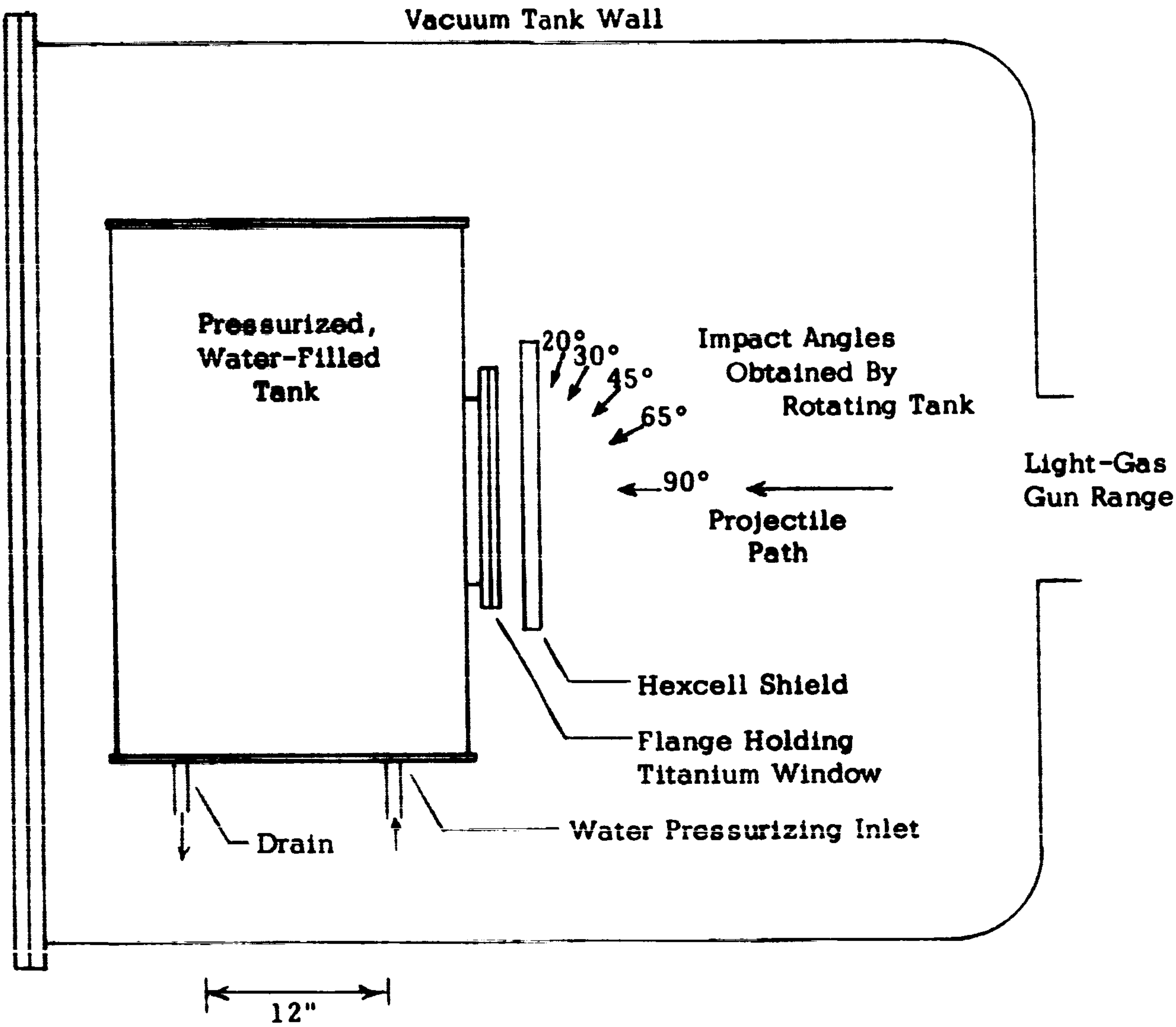


Figure 1.

Schematic Diagram Showing Arrangement of Simulated Spacecraft Tank and Impact Shield

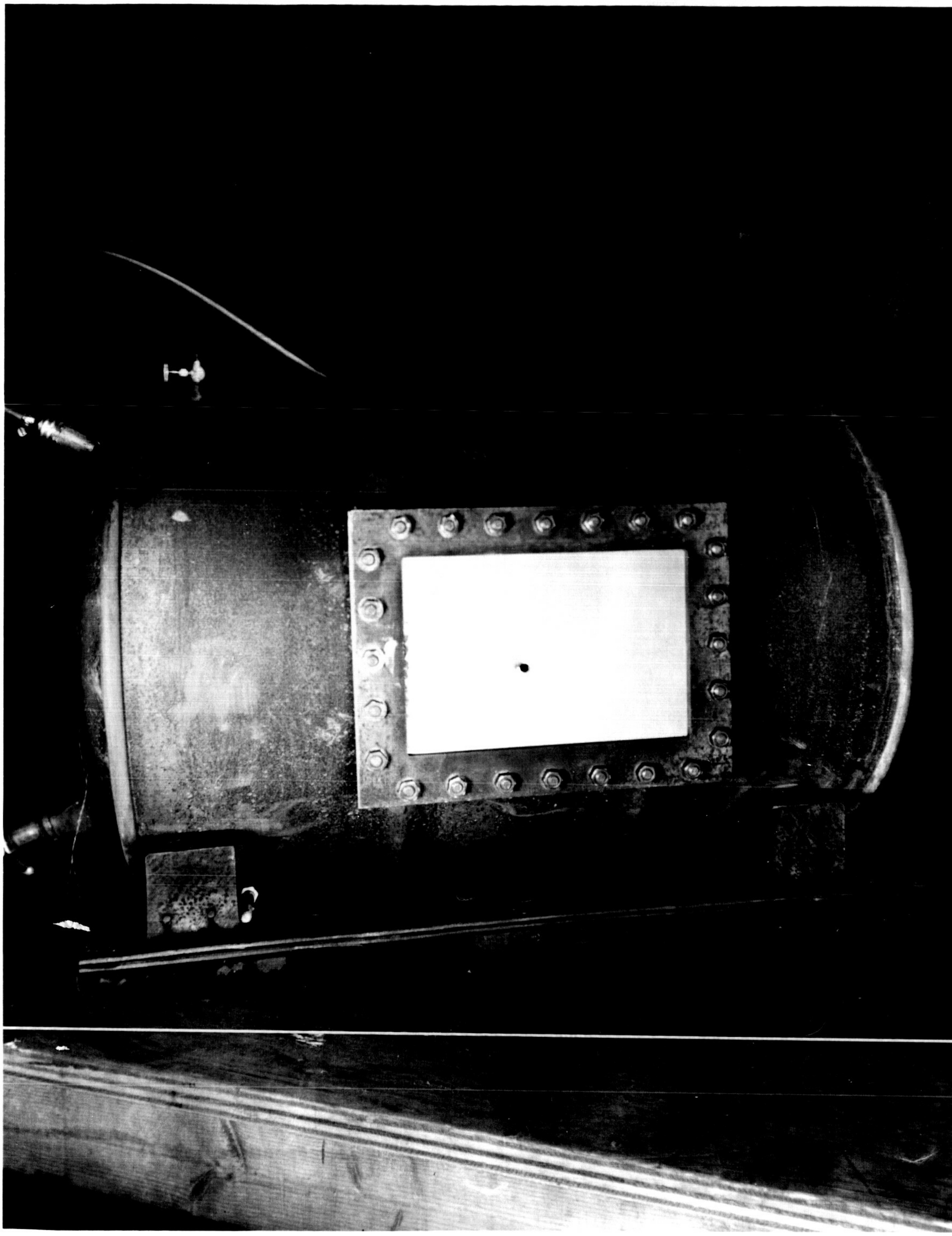
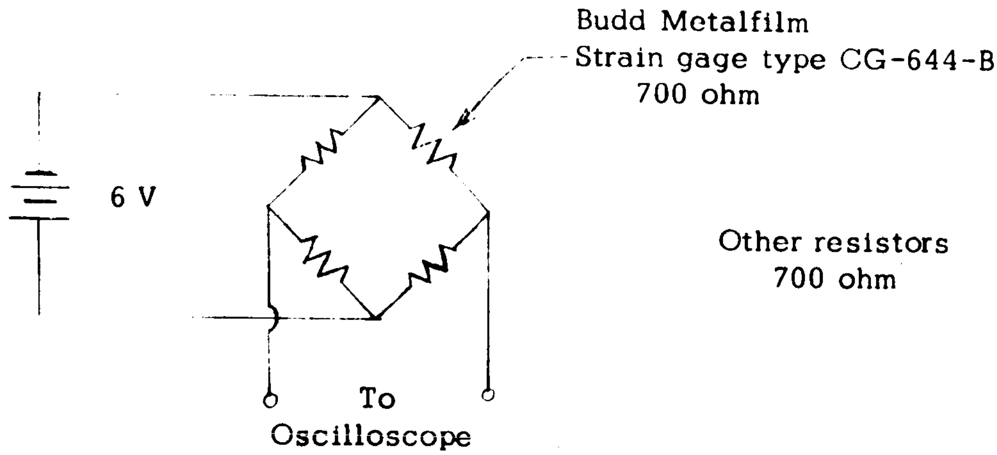
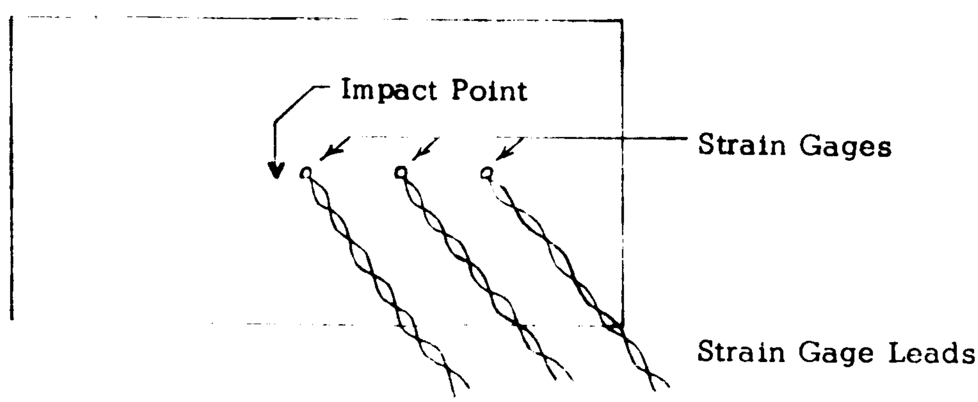


Figure 2.

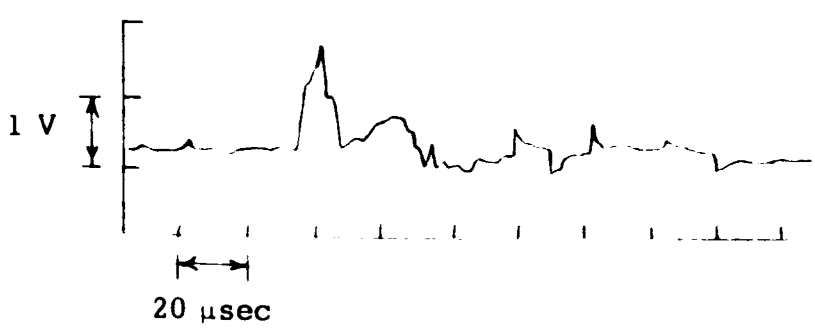
Pressurized, Liquid-Filled Tank
Showing Titanium Window



Strain Gage Circuit



Strain Gage Placement on Tank Window



Tracing of Oscillogram of Strain-Gage Output

Figure 3.

An adequate number of successful strain gage readings was not obtained to plot curves showing the decay of the pressure pulse with distance away from the impact. We did not succeed in getting more than one reading on any one shot due to either failure to obtain impact data or failure of the strain gage to function properly. A tracing of the oscillogram from a properly functioning gage is also shown in Figure 3.

3. SIMULATION OF SPACECRAFT TANKS

The actual spacecraft tanks being simulated are 4' diameter cylinders with a wall of 6Al-4V titanium 0.056" thick. The tanks are pressurized to 180 psi. The hoop stress and longitudinal stress in this tank are given by the following formulae:

$$S_h = \frac{PR}{t} \qquad \text{Hoop Stress} \qquad (1)$$

$$S_L = \frac{PR}{25} \qquad \text{Longitudinal Stress} \qquad (2)$$

where P is internal pressure, R is cylinder radius, and t is wall thickness.

Because of the expense of testing full-size tanks, the tests were to be conducted on small windows on a pressurized tank. To obtain the same biaxial stress on the window as on the full-scale tank, a rectangular window can be chosen. The necessary dimensions and pressure were calculated using the following formulae from Roark, Formulas for Stress and Strain.

$$S_b = \frac{0.75\,\omega\,b^2}{t^2\,(3+4\,\alpha^4)} \qquad (3)$$

$$S_a = \frac{0.054\,\omega\,b^2\,(1+2\,\alpha^2 - \alpha^4)}{t^2} \qquad (4)$$

S_b and S_a are the stresses at the center of a thin plate having length a and width b. The edges are fixed. α is the ratio b/a.

Equations (1) and (2) indicate that $S_h = 2S_L$; therefore for simulation by a flat plate,

$$S_b = 2Sa$$

or

$$\frac{0.75\,\omega\,b^2}{t^2(3+4\,\alpha^4)} = \frac{2 \times 0.054\,\omega b^2\,(1+2\,\alpha^2 - \alpha^4)}{t^2}$$

Solving for α :

$$0.426 = 0.648\,\alpha^2 + 0.108\,\alpha^4 + .864\,\alpha^6 - .432\,\alpha^8$$

A value of $\alpha = 0.667$ satisfies this equation approximately and is convenient for the tank size used since a 12" window was desired. This gives window dimensions 8" x 12". Using this value for α, and the actual titanium window thickness of 0.056", equations (3) and (4) give,

$$S_b = 4040\,\omega \qquad (5)$$

$$S_a = 1865\,\omega \qquad (6)$$

Thus, S_b is approximately 2 S_a as was desired. With α known, equations (1) and (2) can be used with (3) and (4) or (5) and (6) to find the required pressure ω to simulate the stress in the actual tank. We desire S_b = S_h and $S_a = S_L$ where P = 180 psi, R = 24" and t = 0.056".

$$S_b = S_L$$

$$\frac{0.75\,\omega b^2}{t^2(3+4\,\alpha^4)} = \frac{PR}{t}$$

$$\omega = .106\ P = 19.1\ \text{psi}$$

also

$$S_a = S_L$$

$$\frac{0.054\,\omega\, b^2(1+2\,\alpha^2 - \alpha^4)}{t^2} = \frac{PR}{2t}$$

$$\omega = .115\,P = 20.7\ \text{psi}$$

These two pressure values are close enough to justify the use of the approximate value of $\alpha = 2/3$.

We note here that an error was made in the letter report dated 1 November 1964 under this contract in calculating the value of ω to be used. A value of ω = 50 psi was calculated, and all shots were made with this pressure. According to the formulae, this simulates a hoop stress S_h corresponding to a pressure of 471 psi in the actual tank and a longitudinal stress S_L corresponding to a pressure of 436 psi. This gives values of $S_h = S_b$ = 202,000 psi and $S_L = S_a$ = 93,500 psi. This higher value is above the yield stress of the material. Actually the window bulged when pressurized and the stress was reduced from that calculated. The actual stress achieved in the tests is not well known, except that it was undoubtedly close to the yield stress of the material and was somewhat higher than in the actual tanks.

4. TEST RESULTS

In this section, each test shot will be discussed and all the conditions pertinent to the investigation given. The results are summarized in Table I. Photographs of shield and titanium tank wall are included in the Appendix.

TABLE I

DATA FROM TEST SHOTS

Shot No.	Velocity (ft/sec)	Proj. Diam.	Impact Angle	Shield Spacing	Impact Damage and Test Results
15	20,900	3/16"	90°	No Shield	The projectile penetrated titanium forming a clean, round hole 1/2" in diameter. Outward bulging extending to a distance of 2" from the hole was observed. A small hole away from the projectile impact area was probably caused by a fragment chipped off a baffle plate in front of the target by the sabot.
26	20,300	3/16"	90°	3/8"	Round hole 0.3" diameter shows where the projectile penetrated the outer skin of shield. Two large torn areas were caused by slow-moving piston material. This did not penetrate rear of Hexcell and did not affect titanium. Hole in Hexcell. Jagged hole in the inner skin at the point of emergence. Spall from shielding and pieces of projectile impacted titanium causing numerous pits and scratches covering an area 1.5" in diameter, and penetration entirely through the titanium in three places. Irregular holes 0.1", 0.2" and 0.4" in diameter. Outward bulging around holes.
52	22,200	1/8"	90°	3/8"	Unusual hole, 0.5" diameter, with outward petalling in outer shield face. Irregular hole in core 2.5" diameter. Irregular hole in inner shield about 0.75" diameter. Titanium dented inward by concentrated spray in area 0.75" diameter. Central area pitted 0.012".
53	22,700	1/8"	90°	3/8"	Small entry hole in shield with outward bulging. Small ragged exit hole. Fragments hitting titanium caused small dents to .002" deep.

TABLE I (Continued)

Shot No.	Velocity (ft/sec)	Proj. Diam.	Impact Angle	Shield Spacing	Impact Damage and Test Results
56	22,100	1/8"	90°	2"	Small, round hole where projectile entered shield. Larger jagged hole at exit. Titanium splattered with projectile fragments causing indentations to .025" deep.
27	20,200	3/16"	65°	3/8"	Small entry hole in shield with larger ragged exit hole. Titanium was hit by projectile causing irregular hole 1/4" x 3/16".
34	20,200	3/16"	65°	No Shield	1/2" hole in titanium. Outward bulging around hole.
51	22,300	1/8"	65°	3/8"	Small entry hole in shield with large ragged hole at exit. Fragments struck titanium causing splatter and indentations to .043". Large, irregular hole in face of shield caused by piece of piston which did not penetrate the shield.
62	20,700	1/8"	65°	2"	Round entry hole in shield with ragged exit. Fragments struck titanium causing indentations to .007" deep. Other holes in shield caused by pieces of sabot.
64	22,300	3/16"	65°	2"	Irregular entry hole in shield caused by fast-traveling sabot. Large, ragged exit hole. Fragments on titanium caused numerous indentations - the deepest .009".
35	20,000	3/16"	45°	3/8"	Ragged entry hole on shield with outward petalling. Larger ragged exit hole. Considerable spall from shield and large dent .021" deep. Same small indentations up to .032" deep.
40	22,000	3/16"	45°	No Shield	Large, egg-shaped hole in titanium with outward bulging around impact.

TABLE I (Continued)

Shot No.	Velocity (ft/sec)	Proj. Diam.	Impact Angle	Shield Spacing	Impact Damage and Test Results
50	21,700	1/8"	45°	3/8"	Smooth, egg-shaped entry hole in shield with ragged exit hole. Titanium was hit by projectile causing irregular hole 1/2" x 1/4". Irregular hole in shield caused by fast-moving sabot which splattered upon titanium leaving small indentations.
61	20,600	1/8"	45°	2"	Ragged entry hole with outward petalling. Large, ragged exit hole. Fragments on titanium caused numerous indentations, some up to .011" deep.
41	21,100	3/16"	30°	No Shield	Large, egg-shaped hole in titanium. Outward bulging around impact.
42	21,200	3/16"	30°	3/8"	Egg-shaped entry hole in shield with large, ragged exit hole. Considerable spray on face of titanium. No indentations larger than .002" deep.
48	21,600	1/8"	30°	3/8"	Egg-shaped entry hole in shield with large, ragged exit hole. Fragments hitting titanium caused indentations to .016" deep.
60	21,900	1/8"	30°	2"	Egg-shaped entry hole in shield with larger, ragged exit. Fragments hitting titanium caused indentations to .005" deep.
45	21,700	3/16"	20°	No Shield	Projectile penetrated titanium causing irregular hole 3/8" x 5/16". Sabot struck titanium two inches from projectile impact, causing deep dent.

TABLE I (Continued)

Shot No.	Velocity (ft/sec)	Proj. Diam.	Impact Angle	Shield Spacing	Impact Damage and Test Results
46	21,200	3/16"	20°	3/8"	Elongated entry hole in shield with ragged exit holes. Considerable spray on titanium with a few dents to .006" concentrated in a small area.
47	21,200	3/16"	20°	3/8"	Elongated entry hole in shield with small, ragged exit. Fragments hitting titanium caused a few small indentations to .001" deep.
63	20,400	1/8"	20°	2"	Elongated entry hole in shield with larger, ragged exit. Fragments hitting titanium caused indentations to .002" deep.

5. TENSILE TESTS

In an attempt to determine any weakening of the tank skin due to impact damage, strips of the skin were cut from the damaged region and tensile tested per FED. TEST METHOD STD. NO. 151A.

Figure 4 shows the types of failure that occurred in the samples subjected to the tensile test. Table II gives all pertinent data concerning the tensile tests. Photographs of the tensile test specimens are included in the Appendix. It should be noted that all of the control samples, 1 through 6, displayed a classical failure and that considerable damage was necessary to upset this type of failure in the test samples.

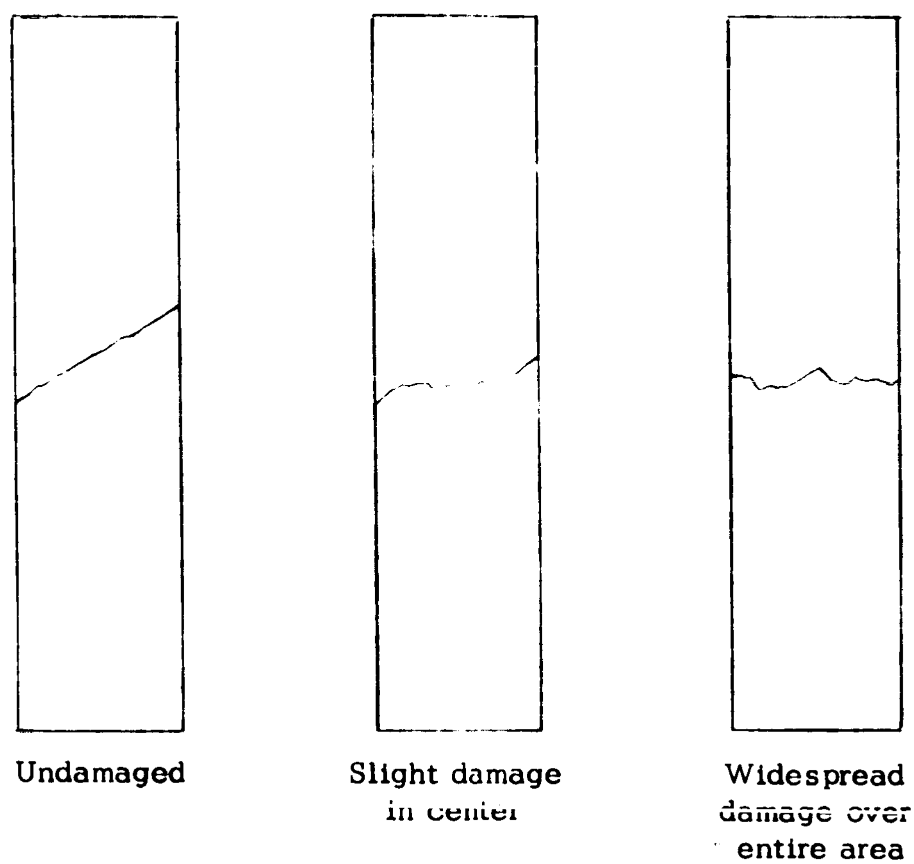


Figure 4.

Typical Breaks in Tensile Test Specimens of Titanium Window Material

TABLE II

RESULTS OF TENSILE TESTS PERFORMED ON SAMPLES
CUT FROM DAMAGED AREAS OF TITANIUM TARGETS

Sample	Size	Area	Ult. Load	Yield Load	Tensile	Yield	Elongation
1	.057 x 1.480	.084	12,400 Lbs.	11,700 Lbs.	148,000 psi	140,000 psi	14.5%
2	.057 x 1.475	.084	12,300 Lbs.	11,600 Lbs.	147,000 psi	138,000 psi	14 %
3	.057 x 1.470	.0835	12,350 Lbs.	11,700 Lbs.	148,000 psi	140,000 psi	15 %
4	.057 x 1.510	.086	12,600 Lbs.	11,750 Lbs.	147,000 psi	138,000 psi	12 %
5	.057 x 1.510	.086	12,600 Lbs.	11,750 Lbs.	147,000 psi	138,000 psi	13.5%
6	.057 x 1.475	.084	12,500 Lbs.	11,500 Lbs.	149,000 psi	137,500 psi	12.5%
	The following results are from the plates that have been tested.						
42	.054 x 1.570	.085	12,600 Lbs.	11,850 Lbs.	148,000 psi	140,000 psi	12 %
35	.055 x 1.565	.086	11,200 Lbs.		130,000 psi		4.5 %
46a	.062 x 1.588	.098	14,750 Lbs.	14,100 Lbs.	151,500 psi	144,000 psi	17.2%
46b	.061 x 1.585	.0965	14,500 Lbs.	14,250 Lbs.	151,000 psi	148,000 psi	4.7 %
47	.061 x 1.574	.096	14,700 Lbs.	14,000 Lbs.	153,000 psi	146,000 psi	17.0%
48	.053 x 1.510	.080	11,350 Lbs.	11,000 Lbs.	141,800 psi	138,000 psi	5.0 %
51	.056 x 1.615	.090	12,700 Lbs.		141,000 psi		3.0 %
52	.060 x 1.530	.091	11,850 Lbs.		131,000 psi		4.5 %
53	.051 x 1.564	.080	11,060 Lbs.	10,750 Lbs.	138,000 psi	134,600 psi	15.5%
62	.062 x 1.750	.108	15,100 Lbs.		139,000 psi		6.0 %
64	.061 x 1.625	.099	14,800 Lbs.	14,400 Lbs.	150,000 psi	145,500 psi	4.0 %
60	.061 x 1.670	.102	15,050 Lbs.	14,500 Lbs.	148,000 psi	142,500 psi	1.5 %
61	.059 x 1.650	.097	15,000 Lbs.	14,500 Lbs.	155,000 psi	149,500 psi	6.5 %
63	.060 x 1.645	.098	14,650 Lbs.	14,250 Lbs.	149,500 psi	145,500 psi	14.5%
56	.056 x 1.650	.092	13,000 Lbs.		142,000 psi		3.0 %

6. DISCUSSION OF DATA

It is evident from the tests, that the Hexcell shielding affords considerable protection to the spacecraft tank. In an unshielded impact, the projectile penetrated the tank at each angle and the damage was about the same at each velocity over the narrow range used.

No disruptive fracturing of the tank was observed even though the pressure pulses were high enough to cause severe outward bulging around the point of impact and the stress level in the material was close to the yield point, particularly at the center of the tank window. In one shot, which was not included as a data shot, the window was hit at 90° with projectile, four pieces of sabot and the shear disc. The pressure pulse was so severe that the window was bulged out to the restraining flanges and was close to being sheared out by the flange at one point. Still, no cracking or evidence of disruptive failure occurred.

The effectiveness of honeycomb shielding material to protect against meteoroids is still somewhat inconclusive. It appears that the spacing between the honeycomb material and the titanium skin is of significance. In every instance where the shielding was spaced 3/8" from the titanium, considerable damage was noted. In some instances particles were still of sufficient size, were traveling fast enough, and were grouped close enough together to penetrate the vessel. In each instance where a 2" spacing was used, the projectile was broken up and dispersed at such an angle as to prevent concentrated damage and actual penetration of the titanium. Some cratering was observed but this could not be considered significant in contributing to the failure of the sections tested. It would appear that further studies involving effectiveness of spacing is warranted.

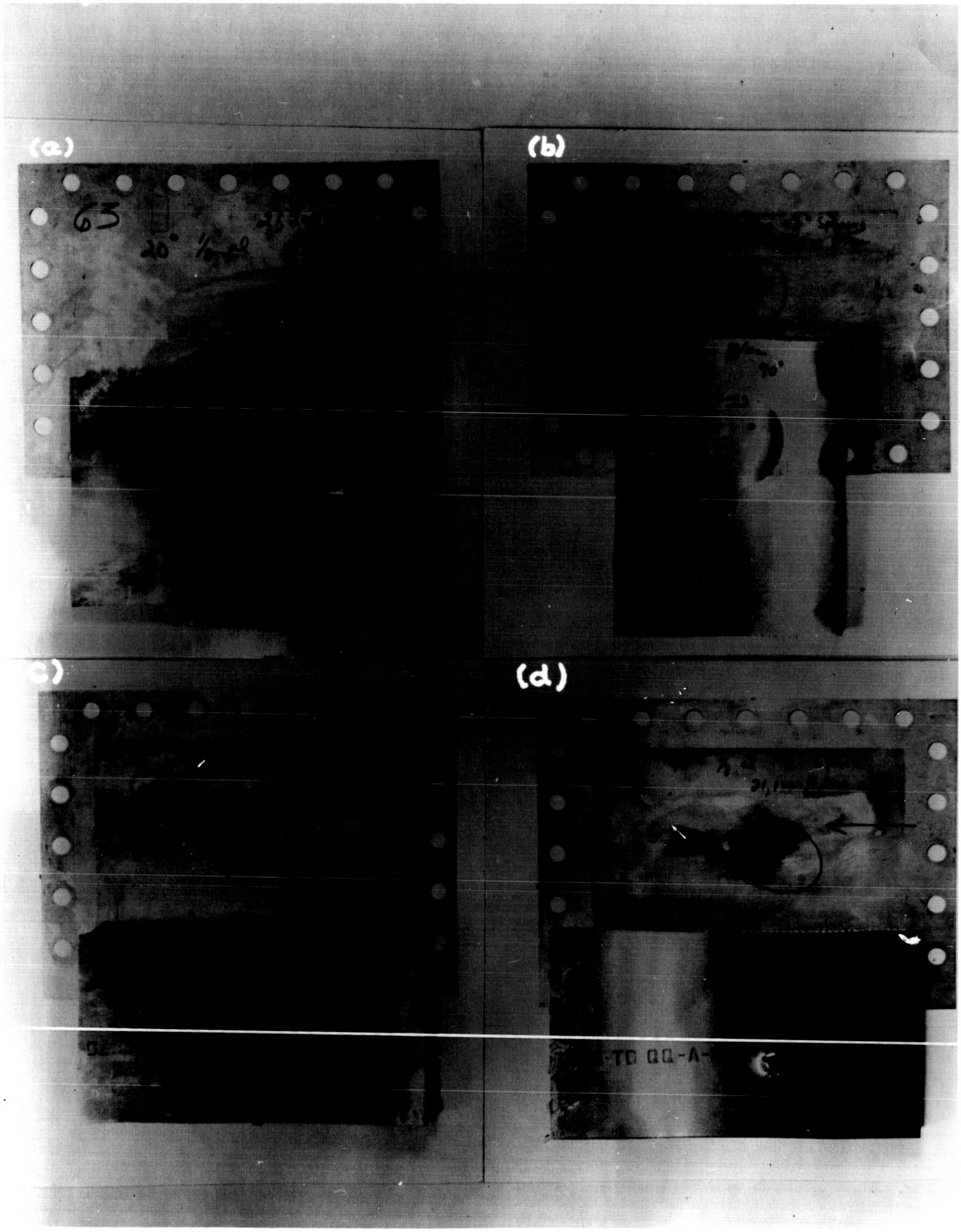
The tensile tests conducted on damaged sections seem to indicate that near penetration of the titanium is necessary before critical failure points of the titanium are reached. Not enough samples having only one or two craters were obtained during this program to make conclusive statements as to probability of failure due to the presence of these isolated craters. All craters studied were in such numbers and grouped so closely together that only the largest ones could be measured.

It appears that the angle of impact has considerable effect upon the condition of the projectile as it emerges from the shielding. The projectile was most broken and damage to the tank least where impact was made at the small angles.

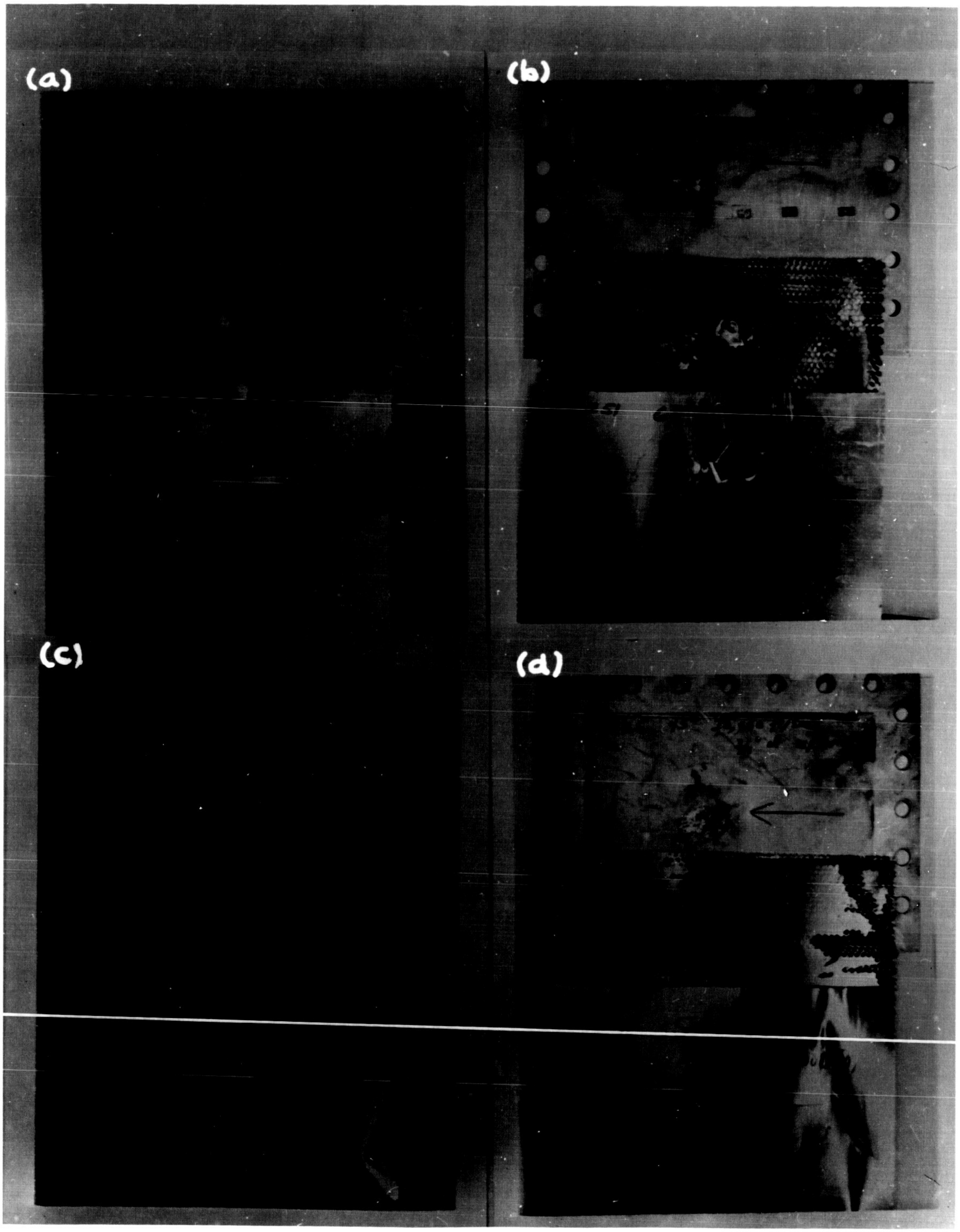
The strain gages provide a suitable measure of relative pressure-pulse amplitudes in the tank skin and can possibly be calibrated for absolute measurements. The time available on the contract expired before strain gage data could be obtained from multiple stations on a single target.

APPENDIX

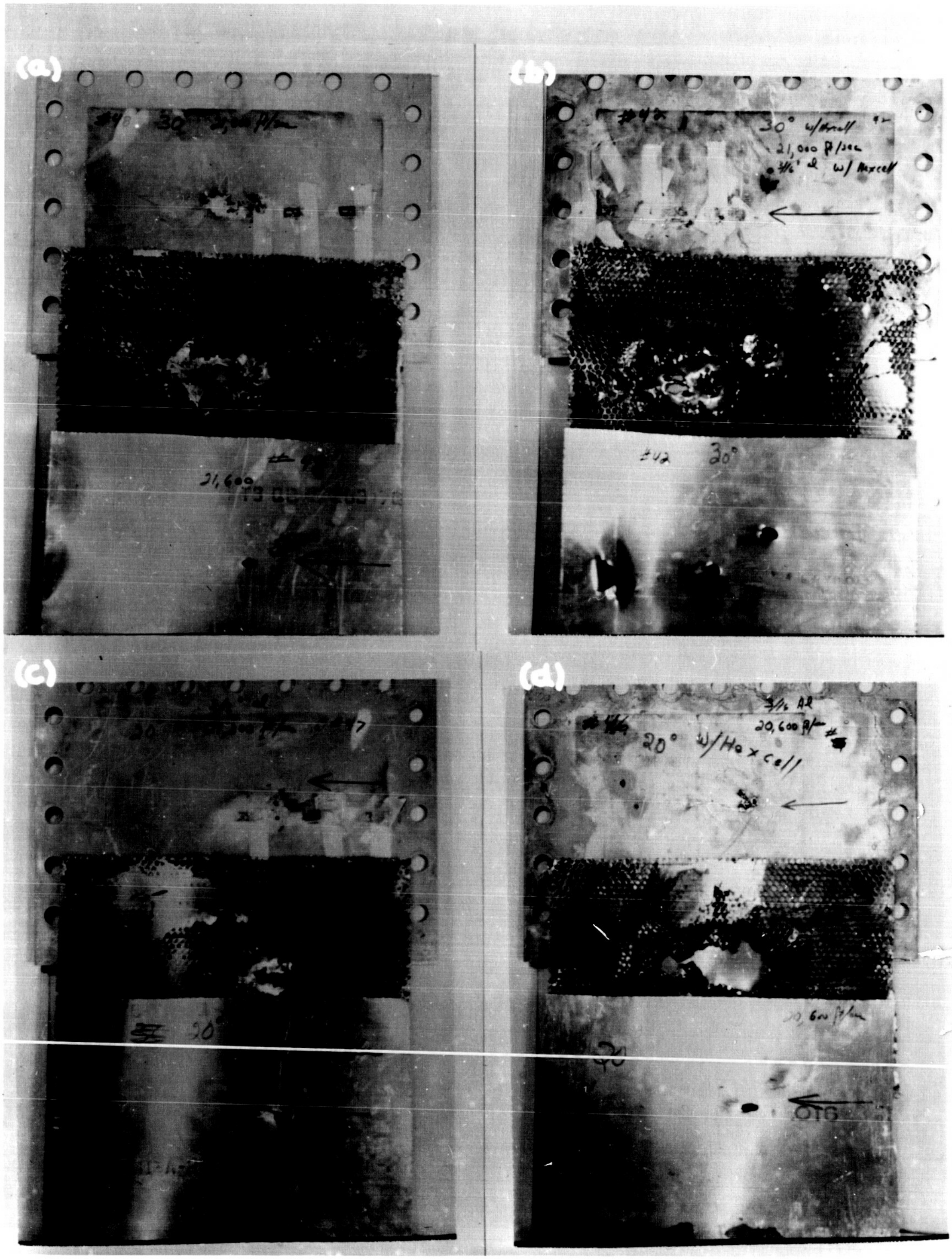
Photographs of Hexcell shield and titanium tank wall showing damage, and photographs of tensile test specimens after testing. In some cases, the aluminum faces of the shield were blown off. In these cases, photographs of the Hexcell core are shown. See Tables I and II for test data.



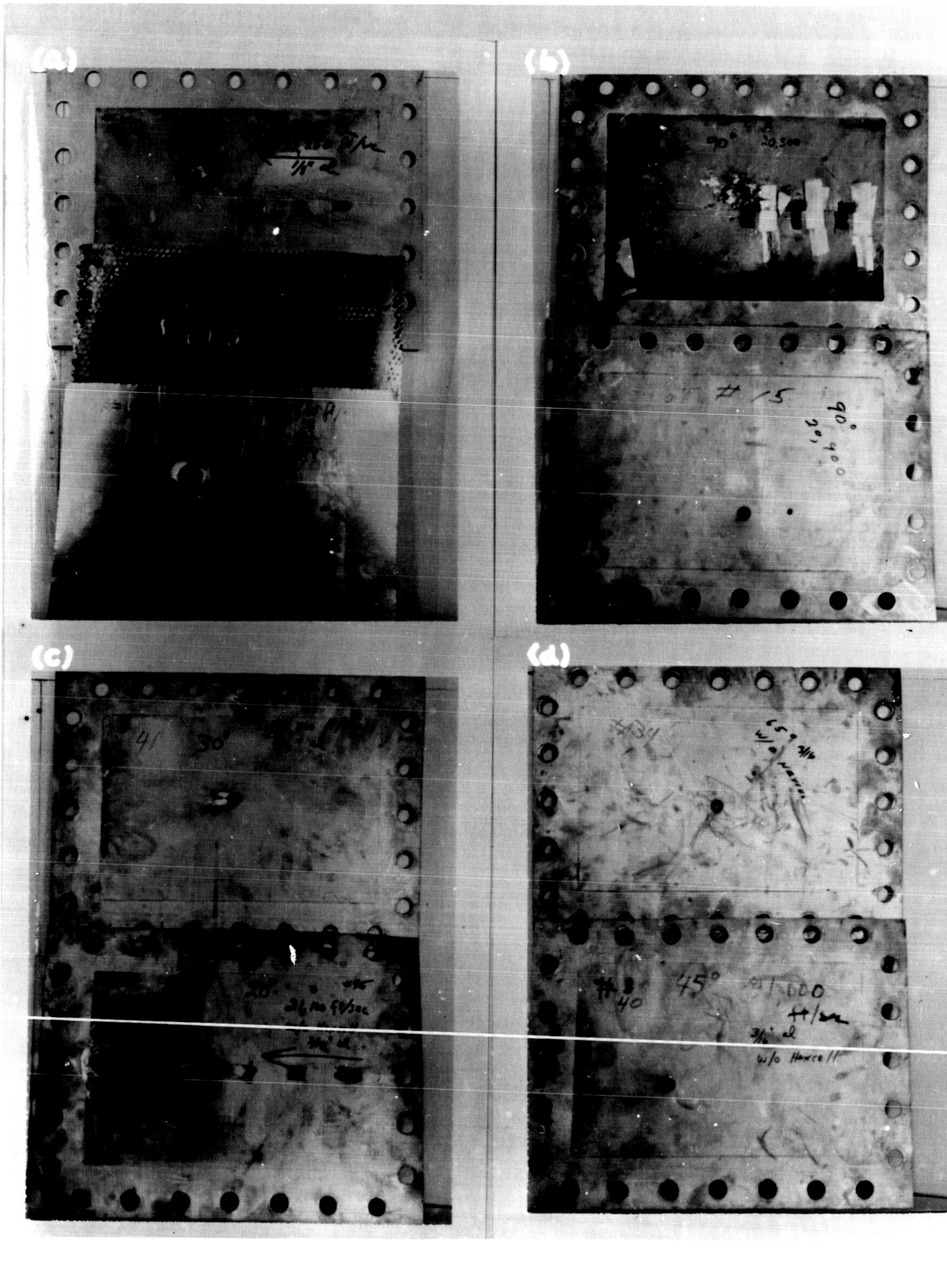
Shot Numbers 63, 56, 60 and 61



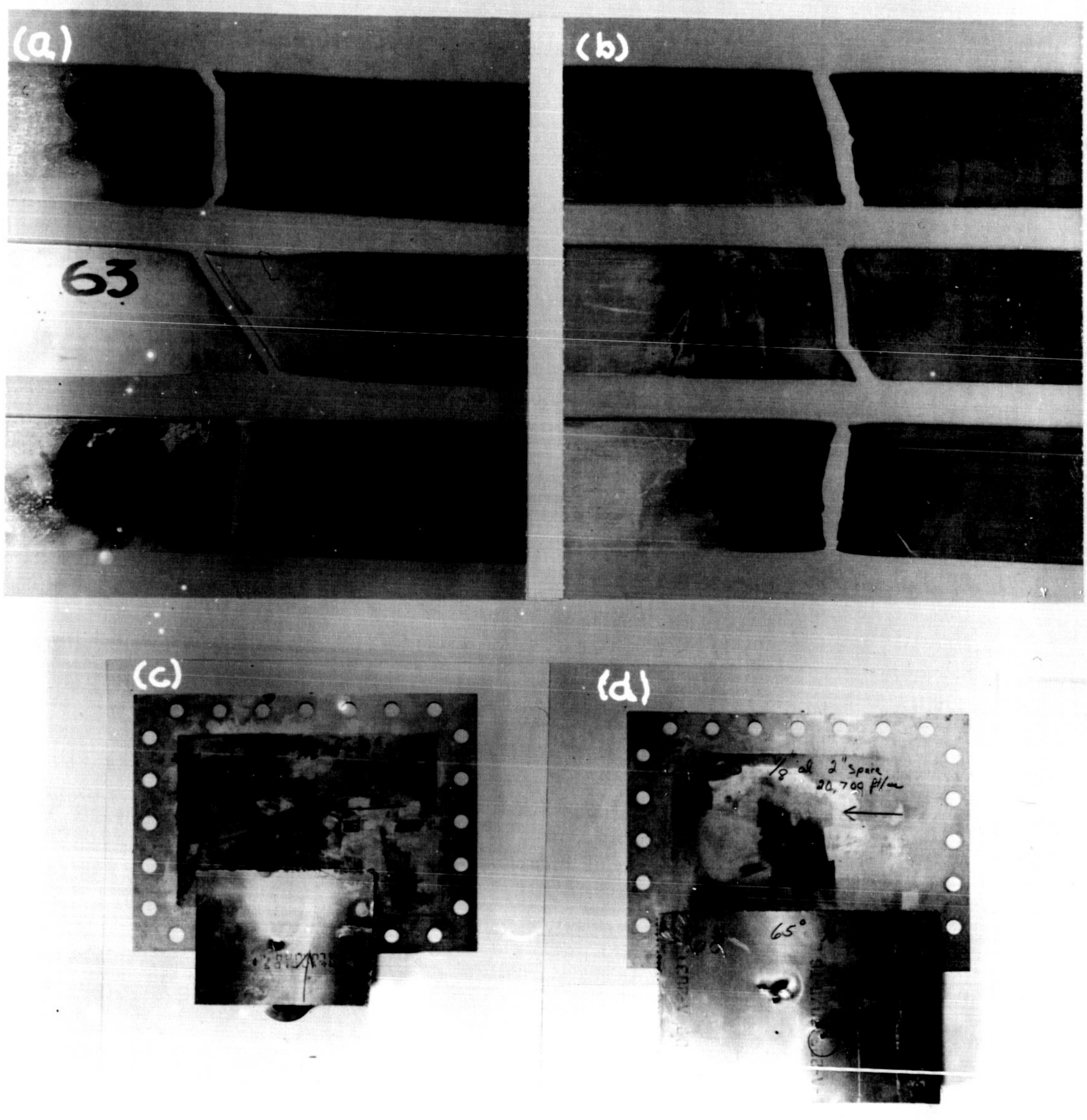
Shot Numbers 27, 51, 50 and 35



Shot Numbers 48, 42, 47 and 46

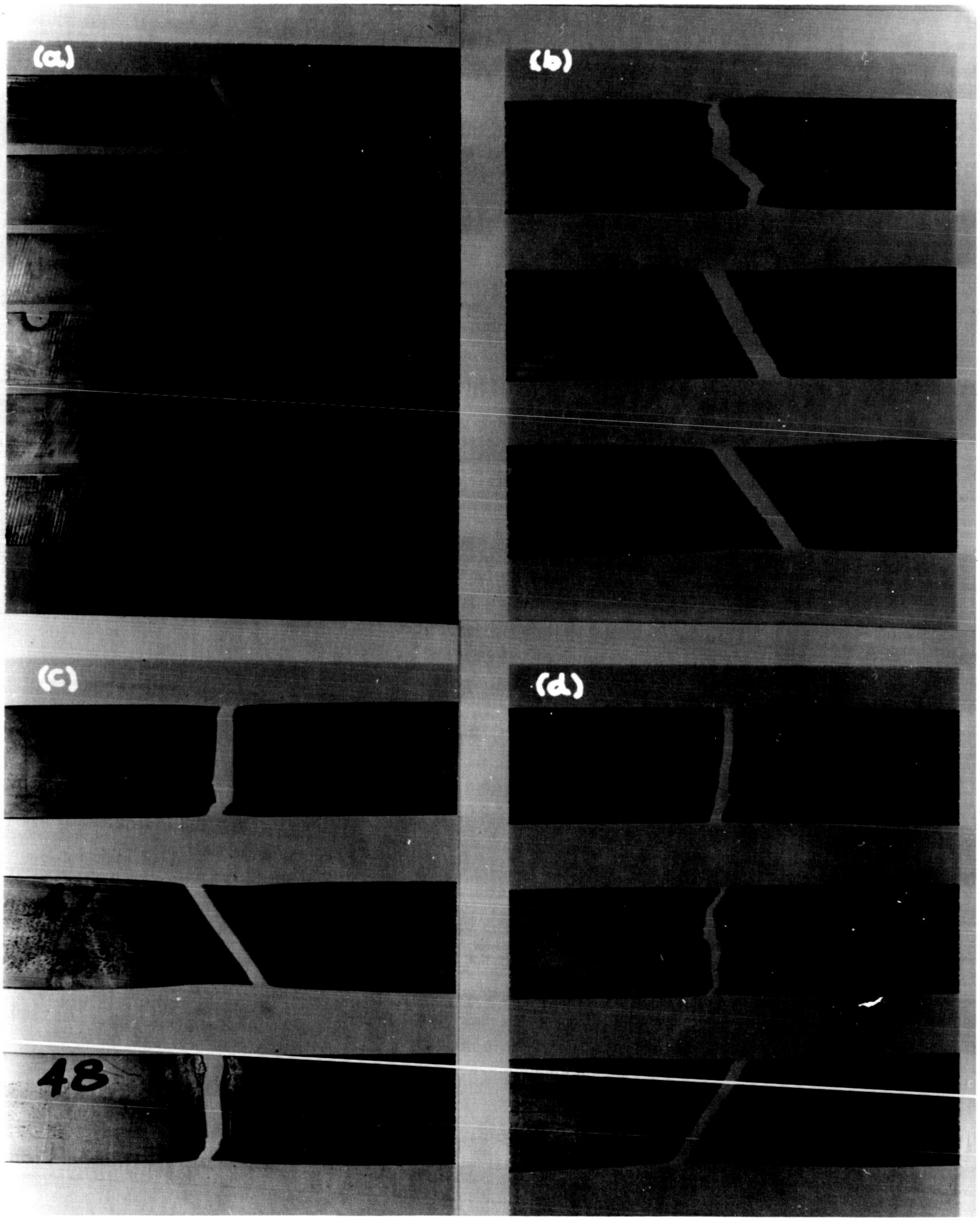


Shot Numbers 52, 26, 15, 41, 45, 34 and 40



a & b Tensile Specimens from Shot Numbers 60, 61, 62, 63, 64 & 65

c & d Target Specimens from Shot Numbers 62 and 64



Tensile Specimens

Controls Numbered 1, 2, 3, 4, 5 and 6
Shot Numbers 35, 42, 46a, 46b, 47, 48, 51, 52 and 53